# Circuit Integration and Circuit Demonstrations

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Naval Research Laboratory

DARPA / MTO High Frequency Integrated Vacuum Electronics (HiFIVE) Industry Day

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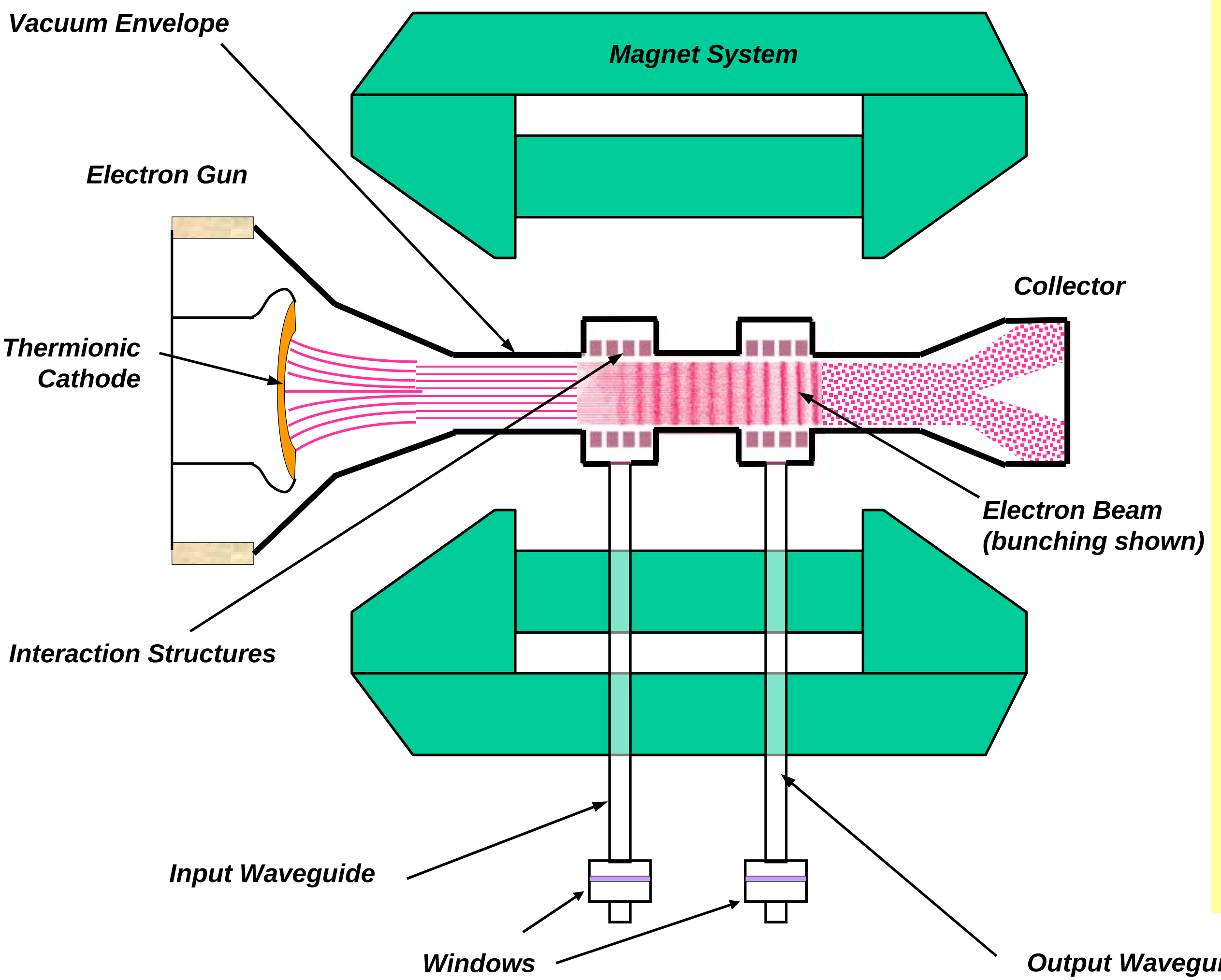
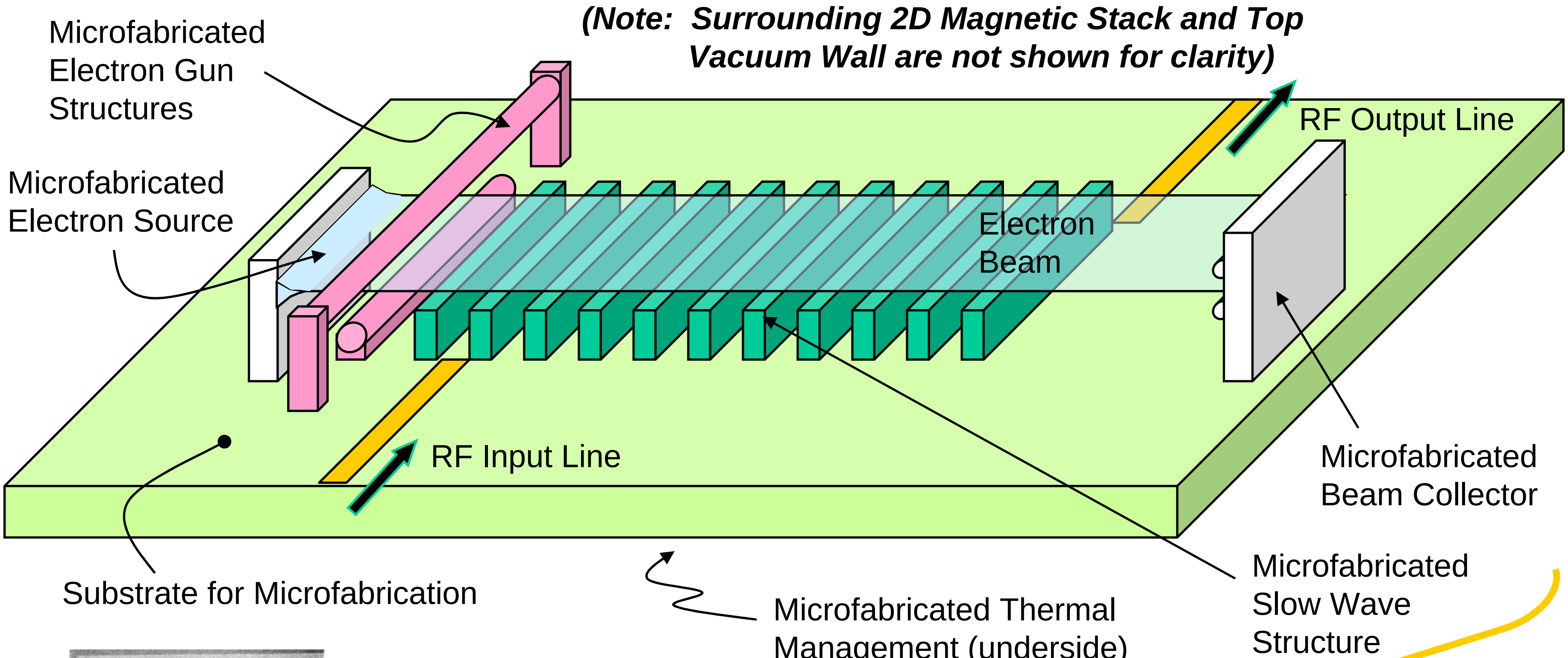
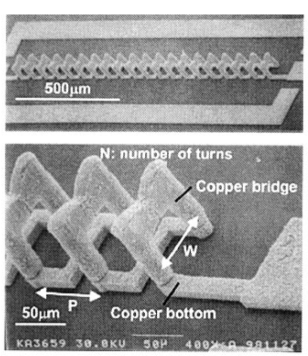
# Background on Integration - Conventional Methods



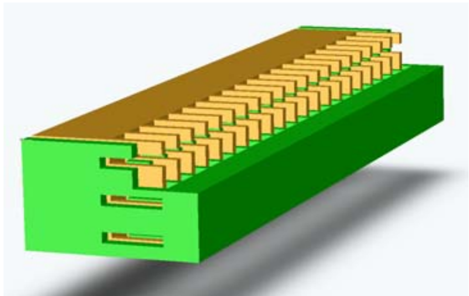

- Interaction structure / vacuum envelope fabricated from various pieces and brazed or welded together
- Cathode: Pressing, sintering, machining, impregnating, coating, activating
- Electron gun fabricated with many manual steps, including numerous welding & brazing operations
- Joining of electron gun, collector, and input/output windows to interaction structure via seal rings, welding
- Hand attachment and tweaking of magnets

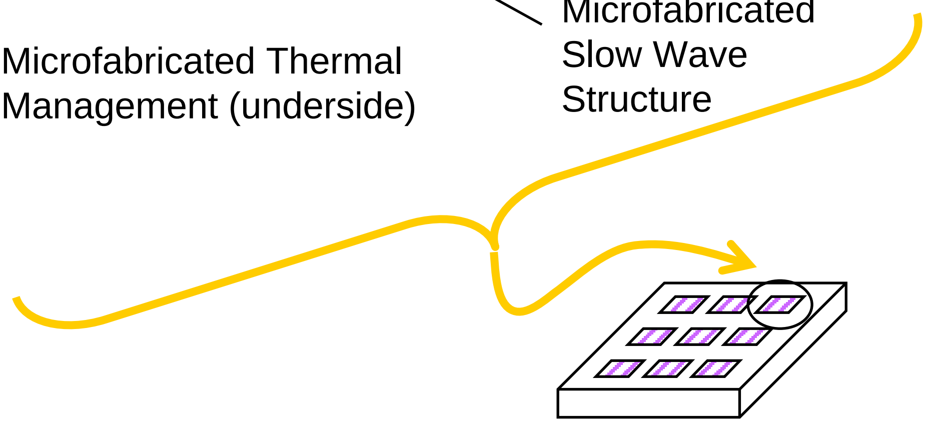
# Integration – Revolutionary Opportunities



Metal MEMS

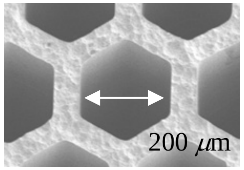
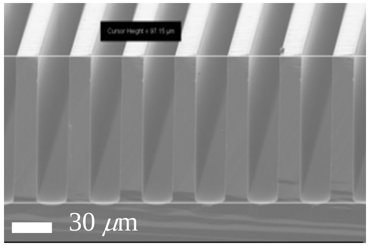
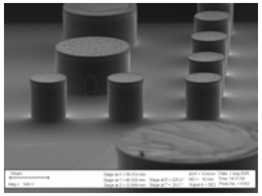
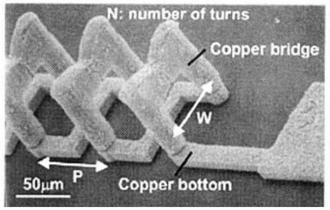
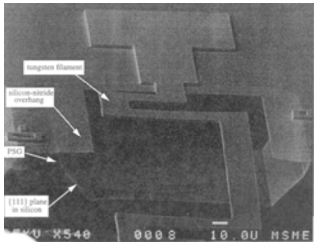

Multi-Layer Bonding


**Tile Architecture Array**

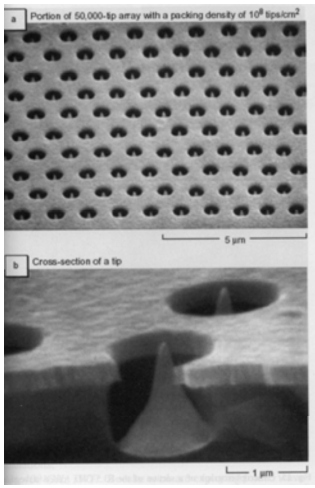
# Some Benefits of Integration

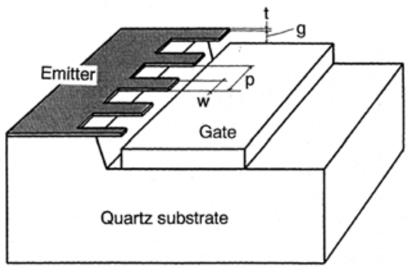
- Self Alignment on Common Substrate
  - Electron Source, Beam, Interaction Structure, Collector
  - Vast Improvement in Achievable Mechanical Tolerance, Overall Yield
- Elimination of Most Manual Assembly Steps
- Ability to also Microfabricate Thermal Management Network on Rear Side of Substrate
- Potential for Many Devices on a Single Large Wafer
- Manufacturing Economies of Scale
- Also Provides a Path to True THz Vacuum Electronics

# Integration Enablers – Circuit Microfabrication

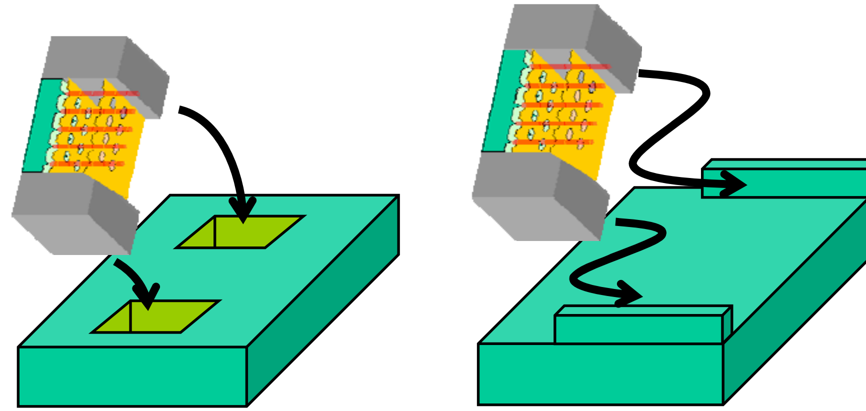
| | LIGA | DRIE | Other MEMS Processes |
|---|---|---|---|
| | <br> | <br> | <br> |
| Vertical Depth Range | 5 to 1000 $\mu$m | 2 - ~ 400 $\mu$m<br>(5 - 200 $\mu$m easy) | 1 – ~ 80 $\mu$m<br>(1- 20 $\mu$m easy) |
| Min. Horizontal Feature Size | 10 $\mu$m | ~ 5 $\mu$m | ~ 2-3 $\mu$m |
| Aspect Ratio | 100:1 | 100:1 | ~ 5:1 |
| Tolerance | ~ 1-2 $\mu$m | ~ 0.5 $\mu$m | < 1 $\mu$m |

# Integration Enablers – Cold Cathodes

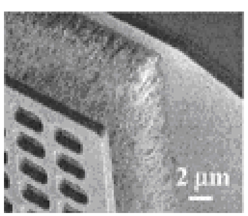


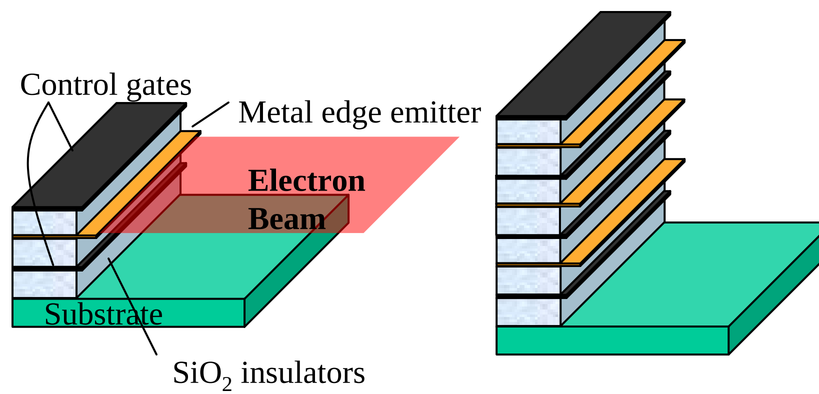

Cold Microfabricated Cathodes



Microfabricated Self Alignment Trenches, Stops, and Structures; MEMS Flip-Up Techniques




Cold Microfabricated Cathodes with Carbon Nanotubes




Configurations that Intrinsically Emit Parallel to the Substrate Plane

# Program Demonstrations

- **Phase I**
  - Demo 1A:  Beam Stick
  - Demo 1B:  Cold Test
- **Phase II**
  - Demo 2A:  High Power Amplifier
  - Demo 2B:  Advanced Cathode
- **Phase III**
  - Demo 3:  Fully Integrated HPA

# Demo 1A: Beam Stick

- **Beam Formation and Transport**
  - Demonstrate Creation and Propagation of a High Aspect Ratio Electron Beam
  - Sheet, Annular, or Multiple Beams
  - Propagate through Volume (Transverse Size, Length) Consistent with Eventual RF Circuits
- **Electron Source / Gun / Collector**
  (need not be the advanced cathode)
- **Magnetic Field System**
- **Critical Issue is Control / Prevention of Electron Beam Instabilities (and Associated Interception)**
  - Curling of Beam Edges (Diocotron Instability)
  - Beam Breakup

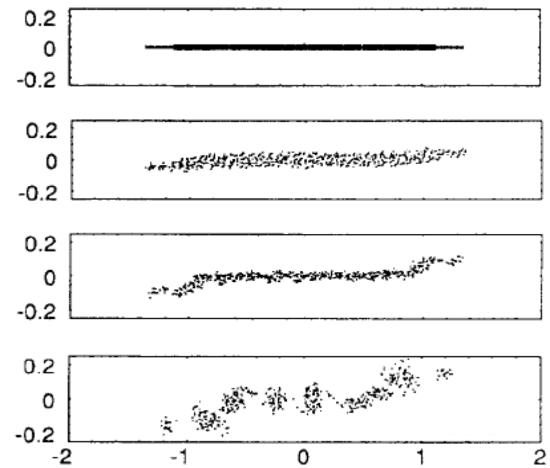
**Go/No-Go Metrics**

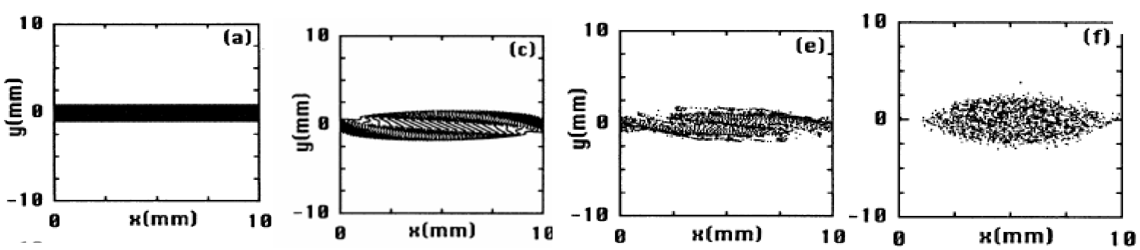
**Beam Voltage: 20 kV**

**Circuit Current Density: 750 A/cm$^2$**
**(in Beam Stick, pulsed is OK)**

**Beam Aspect Ratio: 25**

**Beam Transport Efficiency: 95%**



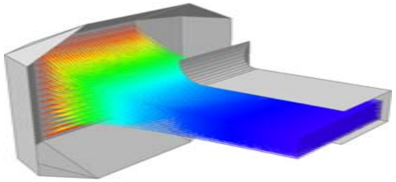



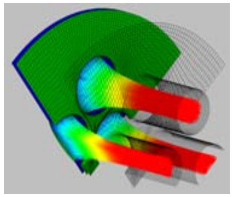
# Government Laboratory Validation of Beam Stick Demo (1A)

*After beam stick testing at performer facilities…..*

- **The beam stick (or a copy thereof) as well as testing procedures and description of the required testing equipment shall be delivered to the Government**
  - Independent Government testing will be performed using suitable high voltage power supplies (modulators) and current/voltage diagnostics
  - Verification that Go/No-Go metrics have been met
- **Performer will also provide design details on the beamstick electron source (electrode & cathode shapes, characteristics), beam tunnel geometry, and magnetic confinement system (magnet and pole piece sizes, compositions, field strengths)**
  - The Government will perform independent analysis using electron trajectory codes, to compare with beam stick testing

Test Bed with 20 kV Modulator at NRL



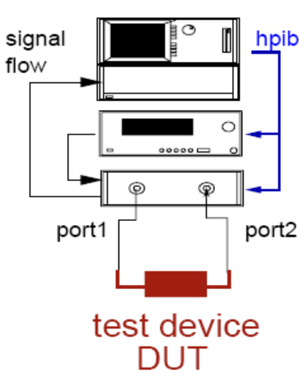


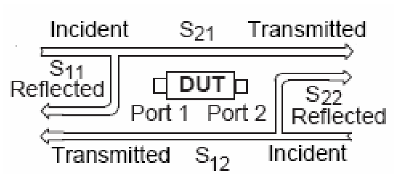
Beam Trajectory / Dynamics Modeling at NRL

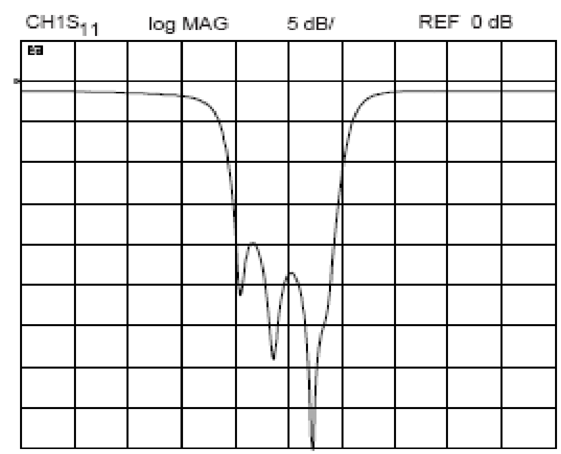
# Demo 1B: Cold Test



- **Demonstrate that the Microfabricated Interaction Structure Provides Required Electromagnetic Characteristics**
  - Frequency Response
  - Transmission / Reflection
  - Dispersion / Resonance
- **Compare to Electromagnetic Simulation Codes**
- **Accuracy / Tolerance**
- **Consistent with Control of Parasitic Electromagnetic Modes (Mode Competition)**



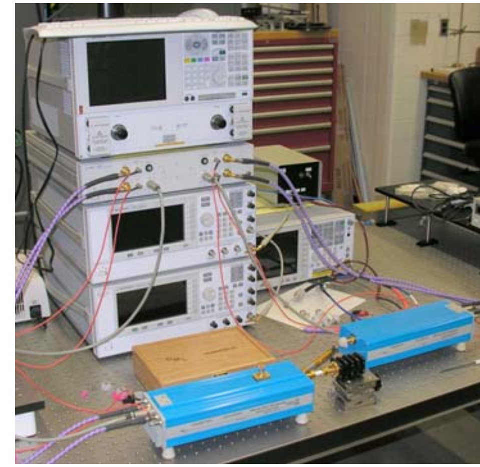



# Government Laboratory Validation of Cold Test Demo (1B)

*After cold testing at performer facilities……*

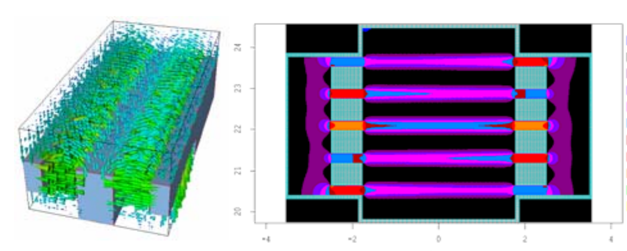
- **The interaction structure (or a copy thereof) shall be delivered to the Government**
  - Cold test behavior will be independently measured and evaluated
- **Performer will provide dimensions and drawings for the structure, so that electromagnetic models can be independently created**
  - Simulations will be performed by the Government to verify behavior and compare to cold test results
- **Performer will provide the Government with a preliminary electrical design for the Phase II HPA sufficient in detail to establish that these structures as tested are consistent with achieving the Phase II objectives**
  - Simulations will be performed with large signal beam-wave interaction simulation codes to verify design, including parasitic EM mode control



Upper-MMW Vector Network Analyzer and Cold Test Facilities at NRL

140-220 GHz

220-325 GHz



EM Simulations of Upper-MMW Structures at NRL

# Demo 2A:  High Power Amplifier

- **HPA Device to Include a Demonstration of all Necessary Circuit Elements and Components**
  - Interaction Structure
  - Electron Source and Electron Gun (need not be the advanced cathode)
  - Magnetic Confinement System
  - Efficient Beam Collector
  - MMIC First Stage Driver
  - Thermal Management Approach
- **Goal is to Prove the Validity of the Overall Circuit Design that will Result in an Extremely High Power Bandwidth Product**
- **Thermal Management Validated by a Minimum of 100 hours of Continuous-Wave Operation of the HPA**

**Go/No-Go Metrics**

**Output Power:  50 W**
**(average power at 220 GHz, external to device)**

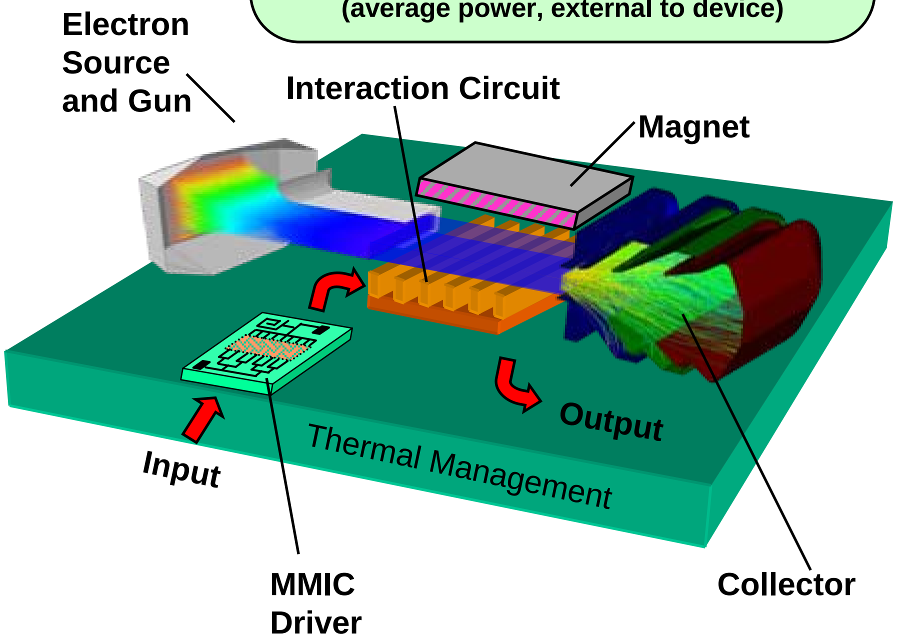
**Bandwidth:  5 GHz**

**Power-Bandwidth Product:  250 W-GHz**

**Efficiency:  5%**
**(total wall-plug efficiency)**

**Spectral Purity:  - 50 dBc**
**(at 250 kHz from carrier)**

**Driver Output Power:  50 mW**
**(average power, external to device)**

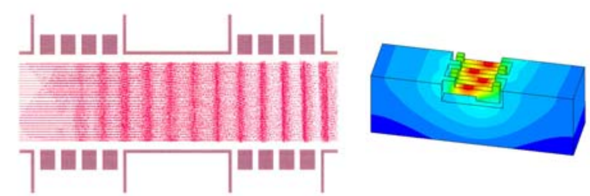


# Government Laboratory Validation of High Power Amplifier Demo (2A)

*After HPA testing at performer facilities…..*

- **The HPA Demo (or a copy thereof) as well as testing procedures and description of the required testing equipment shall be delivered to the Government**
  - Independent Government testing will be performed using suitable high voltage power supplies (modulators) and current/voltage diagnostics
  - Verification that Go/No-Go metrics have been met
  - Verification that no mode competition exists
- **Performer will also provide design details of all the components (electron source, gun, interaction circuit, collector, magnet, MMIC, thermal management scheme)**
  - The Government will perform independent analysis using small and large signal beam-wave interaction simulation codes, as well as thermal analysis codes, to compare with measured performance.

Test Bed with 20 kV Modulator at NRL



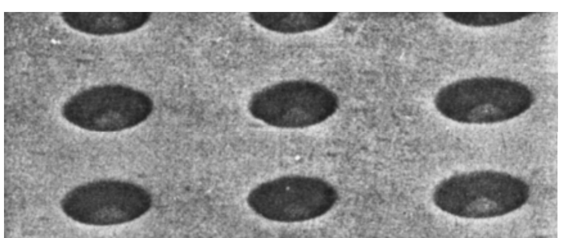
Beam-Wave Analysis and Thermal Analysis Codes at NRL

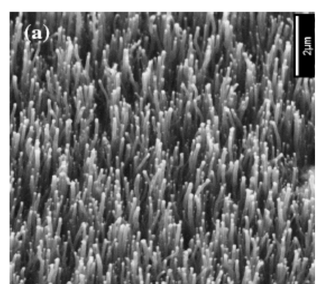
# Demo 2B: Advanced Cathode

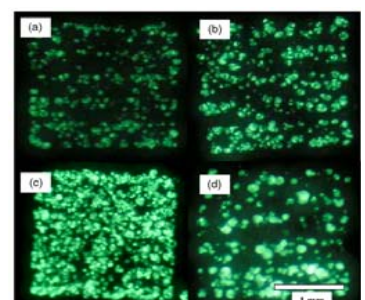
- **Demonstrate an Advanced High Current Density Cathode**
  - Achieve a Current Density Consistent with Circuit Design
  - Characterize Current vs. Voltage
- **Key Issue is Achieving a Long Lifetime**
  - At Least 1000 Hours Lifetime Under Realistic Vacuum and Voltage Conditions
  - Characterize Current vs. Time
- **Cathode must be Suitable for Integration into the HPA During Phase 3**

**Go/No-Go Metric**

**Total Current: 250 mA**
**(as a separate component, measured at the cathode surface, for 1000 hours life)**



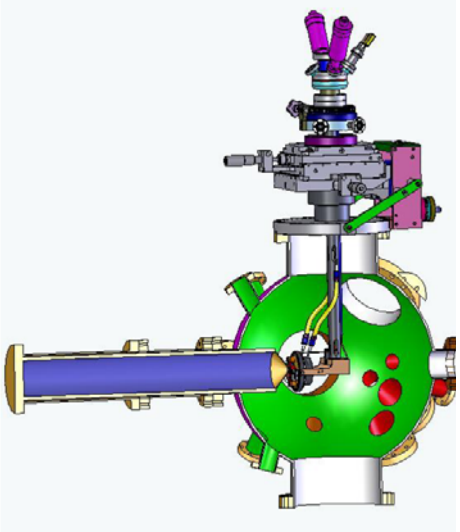


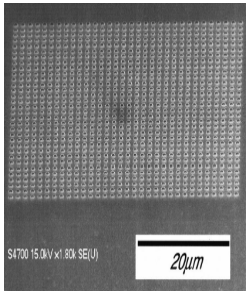



# Government Laboratory Validation of Advanced Cathode Demo (2B)

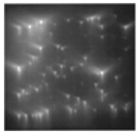
*After cathode testing at performer facilities……*

- **The advanced cathode (or a copy thereof) shall be delivered to the Government**
  - Emission characteristics will be independently measured and evaluated
  - Emission temporal stability and lifetime
  - Current and current density
- **Additional Characterization of a Variety of Relevant Cathode Properties**
  - Emission uniformity
  - Cathode surface chemistry

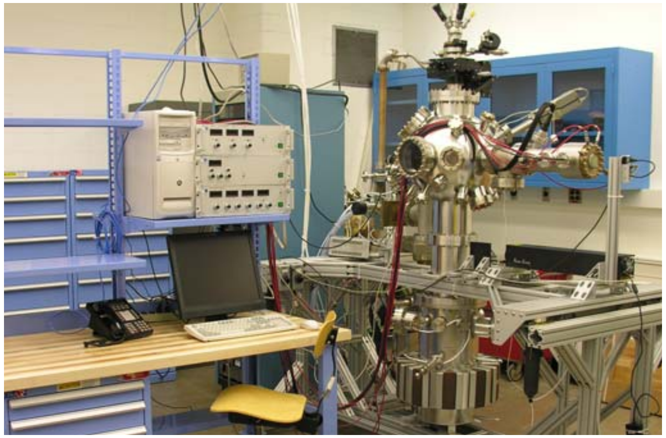





FEA Optical Image



Emission Image



Emission Microscope at NRL

# Demo 3: Fully Integrated HPA

- **Fully Integrated HPA Meeting the Goals of Program**
- **Compact Assembly Including**
  - Advanced High Current Density, Long Life Cathode and Associated Electron Optics
  - High Aspect Ratio Beam(s) and Magnetic Confinement System
  - High Efficiency Interaction Structure
  - Efficient Beam Collector
  - High Power MMIC Driver
  - Thermal Management Approach
- **Demonstrate All Program Performance Metrics Simultaneously**
- **Continuous-Wave Operation of the HPA**

**Final Required Performance**

**Output Power: > 50 W**
**(average power at 220 GHz, external to device)**

**Bandwidth: > 5 GHz**

**Power-Bandwidth Product: > 500 W-GHz**

**Efficiency: > 5%**
**(total wall-plug efficiency)**

**Total Current: > 250 mA**
**(integrated into the HPA)**

**Spectral Purity: - 50 dBc or better**
**(at 250 kHz from carrier)**

**Driver Output Power: > 50 mW**
**(average power, external to device)**

# Government Laboratory Validation of Fully Integrated HPA Demo (3)

*After Fully Integrated Objective Demo HPA testing at performer facilities…..*

- **The Fully Integrated Objective Demo HPA (or a copy thereof) as well as testing procedures and description of the required testing equipment shall be delivered to the Government**
  - Independent Government testing will be performed using suitable high voltage power supplies (modulators) and current/voltage diagnostics
  - Verification that the final required metrics have been met